VALIDATING SOIL PHOSPHORUS ROUTINES IN THE SWAT MODEL

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ABSTRACT. *Phosphorus transfer from agricultural soils to surface waters is an important environmental issue. Commonly used models like SWAT have not always been updated to reflect current understanding of soil P transformations and transfer to runoff. The objective of this study was to validate the ability of routines in both SWAT2000 and SWAT2005 to initialize the quantity of P in different soil P pools (and thus soil total P) and simulate changes in the simulated solution P pool. Based on data from 40 published studies, results show that currently published equations to estimate the soil PSP parameter and SWAT's method of summing four soil P pools underpredict soil total P. An underprediction of soil total could result in underprediction of P loss in runoff with eroded sediment. Conversely, the proposed alternative for estimating soil total P, which includes a new equation to estimate the soil PSP parameter and includes the solution P pool when summing soil P pools, resulted in accurate predictions of soil total P for 484 topsoil samples from 35 published studies. Results also show that both the SWAT routines and the routines proposed by a previous study for simulating changes in soil P were able to accurately predict long-term changes in soil solution P. However, routines in both SWAT2000 and SWAT2005 may underpredict solution P for several weeks after P is added to soils. This could result in underprediction of dissolved inorganic P loss in runoff soon after a P application to soils. The routines proposed by the previous study would not result in similar underpredictions.*

Keywords. Modeling, Phosphorus, Soil, SWAT.

Phosphorus (P) transfer from agricultural soils to P-limited surface waters can accelerate eutrophication, which limits water use for drinking, recreation, and industry (Bennett et al., 2001; Daniel et al., 1998). Over the past 10 to 15 years, substantial effort has been put towards reducing the loss of agricultural P to surface waters. Understanding of the sources and pathways of P transfer has subsequently improved (Gburek et al., 2000; Sims et al., 2000), but computer models used to simulate P transport from agricultural soils to the environment have not always been updated to reflect this improved understanding (Sharpley et al., 2002; Vadas et al., 2006, 2007b).

Computer simulation models represent relatively rapid and cost-effective means to identify agricultural areas in watersheds with a high potential for P transfer to runoff, to quantify the P transfer, and to assess the ability of management practices to minimize the transfer. The SWAT model (Arnold et al., 1998) has been widely used for modeling P loading at the watershed scale, especially from agricultural land uses (Lin et al., 2009; Santhi et al., 2001; Veith et al., 2005). SWAT's soil P routines, which were originally developed for the EPIC model (Jones et al., 1984b), include three inorganic P pools (solution, active, and stable) and two organic P pools

(fresh and humic). SWAT employs user-defined parameters and fixed coefficients to initialize the quantity of these P pools and the rate of P transfer between them. In SWAT, the sum of the active and stable inorganic pools and the fresh and humic organic pools represents total soil P. Because SWAT simulates eroded soil P loss by multiplying predicted soil loss by the concentration of total P in the soil and an enrichment factor, accurate quantification of the quantity of P in the different soil P pools (and thus soil total P) is critical when simulating P loss in erosion. Accurate simulation of the quantity of P in the three inorganic P pools and the rate of P transfer between them is critical for predicting changes in soil solution P. Because solution P is the source for plant P uptake and dissolved inorganic P loss from soils in surface runoff or leachate, it is an important soil P pool to accurately simulate.

Jones et al. (1984a) validated the ability of the originally developed P routines in EPIC to predict changes in solution P with time. Solution P was originally termed labile P for EPIC. However, we are not aware of any efforts to validate the ability of the current P routines in SWAT to initialize the quantity of P in the different pools (and thus soil total P) and simulate long-term changes in solution P. The objective of the present analysis was thus to conduct such validations using routines in both the SWAT2000 and SWAT2005 versions of the SWAT model. Throughout this article, the general name SWAT refers to both SWAT2000 and SWAT2005 when they share the same routines.

VALIDATING INITIAL SOIL P POOL QUANTITIES AND SOIL TOTAL P

Soil P routines in SWAT simulate pools of solution, active, and stable inorganic P (Jones et al., 1984b), and fresh and

humic organic P. SWAT model users must input an initial value for solution P or use the SWAT default value. Because SWAT assigns a default value of only 5 mg kg^{-1} to the initial solution P concentration, it is most accurate for users to input a value. The SWAT documentation does not give guidance on methods for estimating an initial input value for solution P. However, solution P was originally termed labile P in the EPIC model and was quantified through extraction with anion exchange resin (Sharpley et al., 1984). In anion exchange analysis, a soil sample is shaken in a solution of water and an anion exchange resin. Because the solution is initially P-free, the soil desorbs P into the solution, and the resin adsorbs that P. This process is allowed to continue for ~16 h, at which time the resin is removed and its P is extracted and quantified. The amount of P adsorbed by the resin is soil labile P, or solution P in SWAT. Solution P thus represents a combination of inorganic P dissolved in the soil solution and weakly adsorbed to the soil. Any method that extracts P from soil in a physically comparable method as the anion exchange resin can be used to quantify solution P. Examples include the Fe-oxide strip method, as described by Vadas et al. (2006), or isotopic exchange (Frossard and Sinaj, 1998). Because such methods are much more involved than routine soil tests, it is not always practical to conduct them to quantify solution P for a SWAT simulation. However, because P extraction results from routine soil tests, such as Mehlich-3, Bray-1 or Olsen, are often well related to results from these more complicated procedures (Kleinman et al., 2001), it is possible to use routine soil test P data to initialize solution P.

SWAT's active and stable inorganic P are operationally defined soil P pools and were not originally intended to be quantified by specific extraction procedures. Soil active P represents P that is not easily desorbable and is in equilibrium with solution P. Active P is initialized from solution P and a user-defined P sorption coefficient (PSP) as:

$$Active\ P = (Solution\ P)\ (1 - PSP)\ /\ PSP \qquad (1)$$

Soil stable inorganic P is intended to represent strongly sorbed soil P that is in equilibrium with active P and is initialized as four times the quantity of active P.

The PSP in equation 1 represents how much of any inorganic P added to soil remains as solution P upon reaching relative equilibrium with active P. For example, a PSP of 0.4 means 40% of added P remains as solution P and 60% becomes active P. Soil PSP is a user-defined, input parameter in SWAT and is used to initialize the quantity of inorganic P pools and calculate the amount of P that should be transferred between inorganic pools when they are out of equilibrium, which occurs when fertilizer P is added to soil or P is removed from soil through plant uptake or movement with water. Because PSP remains constant once initialized, it is important to input an accurate estimate. As the SWAT documentation describes, PSP values can be determined experimentally by measuring solution P in a soil, adding inorganic P to the soil, incubating the soil for six months, and again measuring solution P. The fraction of added P that remains as solution P is the PSP (Sharpley et al., 1984). However, it is unlikely that model users would perform such experiments to measure soil PSP. If a user does not specify a value, SWAT sets PSP to 0.4, which may be inaccurate for many soils. The SWAT documentation does not provide guidance on how to estimate PSP values, but Sharpley et al. (1984, 1989) developed equations

to estimate PSP from soil properties of soil texture, pH, and base saturation.

SWAT also simulates fresh and humic organic P pools. Fresh organic P is initialized in only the top 10 mm of soil as 0.03% of the residue on the soil surface. Humic P represents that P in stable soil organic matter and is thus much greater than fresh P. In SWAT, humic P is initialized from user-defined soil organic C amounts and by assuming that the C:N ratio of humic substances is 14:1 and the N:P ratio is 8:1. This method for estimating humic P results in similar estimates as equations for estimating soil organic P from Sharpley et al. (1989).

SWAT estimates soil total P as the sum of the active and stable inorganic pools and the fresh and humic organic pools. Assumedly, SWAT does not include inorganic solution P because this pool represents P that is dissolved in the soil solution and not physically adsorbed to soil. According to this logic, solution P would not be lost with eroded sediment and should not be included when estimating soil total P.

To validate SWAT's ability to accurately initialize the quantity of the soil P pools and thus total soil P, we used data from 35 published studies that measured soil P fractions and total P in 484 topsoil samples from 16 different countries (table 1). We first estimated SWAT's solution P from reported soil P extraction data, for which we assumed soil solution P was half of Mehlich-3 P and Bray-1 P, and equal to Mehlich-1 P, Olsen P, Fe-oxide strip extractable P, and anion exchange resin extractable P (Kleinman et al., 2001; Vadas et al., 2006, 2007a). We then estimated soil active inorganic P using reported soil property data, equations presented by Sharpley et al. (1984) to estimate PSP from soil properties, and equation 1. Sharpley et al. (1984) presented separate equations to estimate PSP for highly weathered soils, slightly weathered soils, and calcareous soils. Most of the soils from the 35 studies were highly weathered soils and used the equation:

$$PSP = -0.047 \times \ln(\%\ clay)$$
$$+ 0.0045 \times (Solution\ P,\ mg\ kg^{-1})$$
$$-0.053 \times (\%\ Organic\ C) + 0.39 \qquad (2)$$

Soils from Samadi and Gilkes (1999), Yang and Jacobsen (1990), and Hooker et al. (1980) were calcareous and used the equation:

$$PSP = -0.0061 \times (\%\ CaCO_3) + 0.558 \qquad (3)$$

We imposed upper and lower limits for PSP of 0.95 and 0.05. We then assumed that stable inorganic P was four times that of active inorganic P, according to the SWAT documentation. Because fresh organic P represents only the P in the residue on the soil surface, we assumed this pool was negligible (Radcliffe et al., 2009). We estimated humic organic P using reported soil organic C contents and SWAT's assumptions to initialize this P pool, as stated previously, and then estimated soil total P as the sum of the active and stable inorganic P and humic organic P. An example of these calculations is provided in table 2 for data from Zheng et al. (2003). We then compared measured soil total P to estimated total P.

Figure 1 shows results of measured soil total P and total P as estimated using the SWAT procedures. While there was a good relationship between the two, estimated total P was significantly less than measured total P. We considered three possibilities for this underestimation, and felt that these were

Table 1. Data for 35 published studies used to validate the ability of the SWAT model to initialize soil P pools and total P.

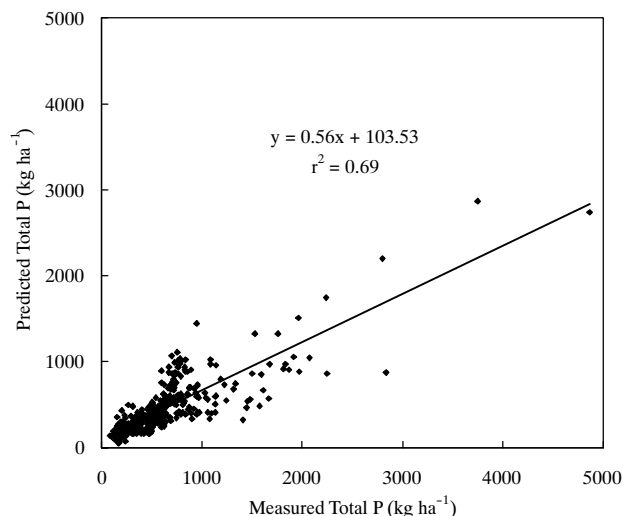| Source	Location	No. of Soils	Total P (mg kg^{-1})
Agbenin and Goladi (1998)	Guinea	7	180-529
Araujo et al. (2004)	Brazil	6	228-391
Barber (1979)	U.S.	6	400-632
Beauchemin et al. (2003)	Canada	3	1189-2076
Beck and Sanchez (1996)	Peru	3	229-436
Blake et al. (2003)	UK	17	300-950
Delgado and Torrent (2000)	Spain	5	705-1400
Delgado et al. (2002)	Spain	6	532-864
Dobermann et al., 2002)	Philippines	14	402-875
Dou et al. (2009)	U.S.	13	808-4866
Garcia-Montiel et al. (2000)	Brazil	11	136-247
Guo et al. (2000)	U.S.	8	528-2098
Hooker et al. (1980)	U.S.	88	148-549
Hountin et al. (2000)	Canada	6	664-1042
Iyamuremye et al. (1996)	Rwanda	2	900-1840
Lilienfein et al. (2000)	Brazil	8	333-567
Maguire et al. (2000)	U.S.	16	205-1596
Nziguheba et al. (1998)	Kenya	2	225-231
Ohno et al. (2005)	U.S.	8	670-1670
Phiri et al. (2001)	Colombia	17	603-893
Reddy et al. (1999)	India	8	484-647
Roberts et al. (1985)	Canada	12	377-768
Rubaek and Sibbesen (1995)	Denmark	3	318-553
Samadi and Gilkes (1999)	Australia	14	83-358
Schmidt et al. (1996)	U.S.	8	206-391
Sharpley and Smith (1985)	U.S.	5	294-953
Sharpley et al. (2004)	U.S.	20	122-627
Subramaniam and Singh (1997)	Norway	8	855-2775
Sui et al. (1999)	U.S.	12	527-2833
van der Salm et al. (2009)	Netherlands	12	511-1031
Whalen and Chang (2001)	Canada	8	920-3750
Withers et al. (2007)	Europe	24	404-1868
Yang and Jacobsen (1990)	U.S.	72	201-607
Zheng et al. (2003)	Canada	5	510-1086
Zheng et al. (2004)	Canada	4	878-931

Figure 1. Measured soil total P and total P predicted using equations proposed by Sharpley et al. (1984) for estimating PSP and the SWAT method of summing four soil P pools.

tion of solution P as a possibility for underestimating soil total P.

The second possibility for underestimation of soil total P was that SWAT does not include solution P when estimating soil total P. Solution P was originally termed labile P for the EPIC model because it was measured by anion exchange resin extraction and is thus a combination of inorganic P dissolved in the soil solution and weakly adsorbed to the soil. Therefore, it is more accurate to include solution P when estimating soil total P. Including solution P in estimating soil total P actually improved the relationship between measured and estimated values, but estimated values were still significantly less than predicted values (predicted total P = 0.70 × measured total P + 62.18, r^2 = 0.75; data not shown).

The final possibility for underestimation of soil total P was that equations 2 and 3 from Sharpley et al. (1984) overestimated PSP values from soil properties, which would result in relatively low estimated active and stable P, and thus underestimated soil total P. To investigate this possibility, we used data from the 35 studies in table 1 to estimate the PSP value that would be needed to exactly calculate measured soil total P. To do this, we first subtracted humic P and solution P, estimated as described previously, from measured total P. The difference thus represented the sum of active and stable inorganic P. We then used the SWAT assumption that stable inorganic P is four times active inorganic P and calculated both active and stable P. Knowing solution and active P, we then used equation 1 to solve for PSP. These PSP values thus represented the values that would be needed to exactly calculate measured soil total P. We then generated a multiple regression equation to relate these PSP values to the same soil

the only three reasons that could have caused underprediction of total P. First was that we underestimated soil solution P from reported soil P extraction data. Underestimating solution P would lead to underestimation of active and stable inorganic P and thus soil total P. In developing the EPIC model, Sharpley et al. (1984, 1989) measured soil solution P by the anion exchange method and developed equations to estimate solution P from more routine soil P tests. Because the methods we used to estimate solution P (i.e., solution P is half of Mehlich-3 P and Bray-1 P, and equal to Mehlich-1 P, Olsen P, Fe-oxide strip extractable P, and anion exchange resin extractable P) would actually provide equal to or greater estimates of solution P than equations originally proposed by Sharpley et al. (1984, 1989), we discounted an underestima-

Table 2. Example of data and calculations used to estimate soil total P for data from Zheng et al. (2003).

Soil	Clay (%)	Organic C (%)	Mehlich-3 P (mg kg^{-1})	Solution P (mg kg^{-1})	PSP	Active P (mg kg^{-1})	Stable P (mg kg^{-1})	Humic P (mg kg^{-1})	Total P (mg kg^{-1})
1	10.1	1.04	57.3	28.7	0.355	52.0	208.1	92.9	353.0
2	19.3	0.95	49.2	24.6	0.311	54.4	217.8	84.8	357.0
3	27.5	1.74	65.2	32.6	0.289	80.3	321.3	155.4	556.9
4	40	1.96	57.4	28.7	0.242	89.9	359.8	175.0	624.7
5	65.6	2.9	71.5	35.8	0.201	142.5	570.1	258.9	971.5

properties used by Sharpley et al. (1984) in equation 2. The resulting equation was:

$$PSP = -0.053 \times \ln(\% \text{ clay})$$

$$+ 0.001 \times (\text{Solution P, mg kg}^{-1})$$

$$-0.029 \times (\% \text{ Organic C}) + 0.42$$

$$(r^2 = 0.35) \qquad (4)$$

The equation is similar to equation 2 but varies in its coefficients, especially for solution P. We found that PSP values calculated using equation 4 and reported data from the 35 studies averaged 0.24. Comparatively, 74% of PSP values calculated with equations 2 and 3 were greater (by an average of 57%) than equation 4 PSP values. This exercise thus showed that using equations 2 and 3 to estimate PSP values for SWAT will result in underestimation of soil total P, given that soil solution P is estimated with the methods we used in this study. We used equation 4 and soil properties reported in the 35 studies in table 1 to re-estimate PSP values. We then re-estimated soil total P following the same procedures described previously, but included solution P when estimating soil total P. The results in figure 2 show that using equation 4 to estimate PSP resulted in predictions of soil total P that were not significantly different from measured values.

These results have potentially important implications when using SWAT to model P loss from agricultural watersheds. The first implication is that SWAT's not including solution P when calculating soil total P will likely result in underestimation of soil total P. This in turn will result in underestimation of soil P lost with eroded sediment, which may cause inaccurate predictions of sediment P loads delivered at the watershed outlet. The second implication is that SWAT users who employ equation 2 or equation 3 to estimate soil PSP may enter PSP values that are too large and will in turn cause initialization of active and stable P pools that are too small, according to equation 1. For example, SWAT uses a default value of 0.4 for PSP. If the actual PSP value for a soil is less than 0.4, but the 0.4 value is input into SWAT, then the model will under-initialize soil active and stable P, and thus soil total P. For data from the 35 studies, 51% of soils would have a PSP value less than 0.4 if equation 2 and 3 are used.
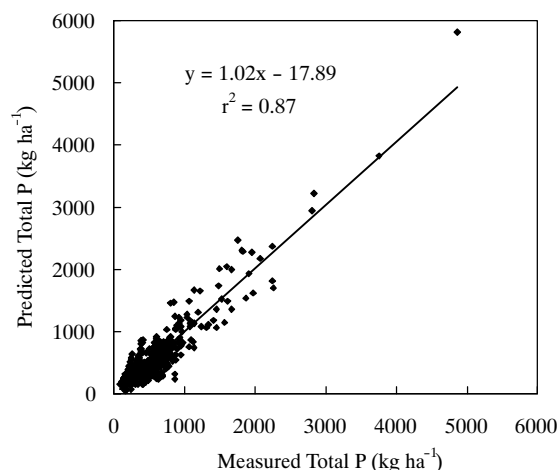

Figure 2. Measured soil total P and total P predicted using equation 4 for estimating PSP and including solution P when summing soil P pools.

If equation 4 is used, this increases to 96% of values. Thus, using SWAT's default PSP value of 0.4 is likely to under-initialize soil active and stable P, and thus soil total P, for many soil types. Because PSP remains a constant variable in SWAT, the relationship between the relative quantities of P initialized between the solution, active, and stable P pools will remain throughout a model simulation. With a constant PSP of 0.4, for example, SWAT will always try to have the ratio of solution P to active P be 40:60. This in turn means that total soil P will remain under-estimated throughout a simulation, which can cause the same problems with underestimation of soil P loss with eroded sediment. Finally, results also show that the methods we used to estimate solution P from commonly reported soil test P data are reasonable, and that equation 4 can reasonably estimate PSP for a wide variety of soil types. For example, for soils examined in the 35 studies, soil clay content ranged from 1% to 90%, soil OC ranged from 0.1% to 14.2%, solution P ranged from 1.1 to 684.5 mg kg^{-1}, and resulting PSP values ranged from 0.057 to 0.740. This range in PSP values shows why it can be more accurate to input a well-estimated value for PSP than use the SWAT default value of 0.4.

VALIDATING LONG-TERM CHANGES IN SOIL SOLUTION P

In SWAT2000, when inorganic P is added to soil, the equilibrium between solution and active P in equation 1 is disrupted. Solution P is relatively too large, and P is moved from solution to active P to re-establish equilibrium. The amount of P moved is equal to the imbalance between the pools:

$$P \text{ moved} = \text{Solution P} - (\text{Active P}) \left[\frac{PSP}{(1\text{-PSP})} \right] \qquad (5)$$

The term (active P)[PSP/(1-PSP)] represents solution P relative to active P at equilibrium. The difference between this value and the actual solution P is the P imbalance between the pools. Because the entire P imbalance is moved, the two pools are still not at equilibrium. SWAT2000 then begins to move P from active to solution P to restore the equilibrium. Each day, 0.1 of this imbalance is moved from active to solution P until the pools reach equilibrium. This 0.1 is thus the P transfer coefficient. Because solution P is the source of dissolved inorganic P loss in runoff, the SWAT2000 P transfer routines mean that any inorganic P added to soil is initially unavailable to loss in runoff and slowly becomes available over time as P is moved from the active to the solution pool. This simulation process is in fact the opposite of what experimental data show actually occurs when inorganic P is added to soil, which is an initially high availability of added P to loss in runoff and a gradual decrease with time (Kleinman et al., 2002; Sharpley, 1982). This suggests that SWAT2000 could underpredict P loss in runoff that occurs soon after a P addition to soils, but still accurately predict long-term changes in solution P (i.e., months to years).

In SWAT2005, the 0.1 P transfer coefficient is applied when P is moved from the solution to the active P pool, but is omitted when P is moved from the active to the solution P pool, which is the opposite of what happens in SWAT2000. When fertilizer P is added to soil in SWAT2005, it is slowly moved from solution to active P, and thus remains more

Table 3. Data for 13 published studies used to validate the ability of the SWAT model to predict long-term changes in soil solution P.

Source	Location	No. of Years	Annual P Fertilizer (kg ha⁻¹)
Alessi and Power (1980)	U.S.	6	0-160
Barber (1979)	U.S.	25	0-54
Beck and Sanchez (1996)	Peru	13	0-80
Dobermann et al. (2002)	Philippines	3	0-354
Eghball and Power (1999)	U.S.	7	0-305
Hooker et al. (1980)	U.S.	5	25-500
Kamprath (1999)	U.S.	14	0-40
Linquist et al. (1997)	U.S.	4	0-510
Reddy et al. (1999)	India	4	0-55
Schmidt et al. (1996)	U.S.	17	0-40
Sharma and Subehia (2003)	India	22	13-78
Whalen and Chang (2001)	Canada	16	0-90
Zheng et al. (2004)	Canada	10	25

available to loss in runoff in the days and weeks after fertilization. These SWAT P transfer routines have been modified from the ones originally developed for the EPIC model. EPIC always used a 0.1 factor in equation 5 to move P from solution to active P or active to solution P.

To validate the ability of the P routines in SWAT2000 and SWAT2005 to accurately predict changes in solution P, we used data from 13 published studies (table 3) from five countries that monitored changes in soil P in agricultural soils over 3 to 25 years. Some of the studies in table 3 were also used in analyses of soil total P, as detailed previously (table 1). To simulate changes in solution P, we used a stand-alone, daily time step, FORTRAN model similar to that described by Vadas et al. (2007b). We chose to not use the actual SWAT2000 or SWAT2005 models because that would have required obtaining climate data for the 13 studies and setting up complex model scenarios. Because SWAT simulates its own crop growth and nutrient uptake, we could not have input the exact crop P uptake measured in the 13 studies, which would have introduced error in simulating changes in solution P. We also could not have simulated the exact depth of the topsoil layer from which reported soil samples were taken and to which fertilizer was added. This would also have introduced errors in simulating solution P. Finally, we also could not have easily changed the SWAT model code to reflect the variability in soil P dynamics that we wanted to evaluate and extract model output data for daily changes in inorganic P pools.

Our soil P model simulated one topsoil layer that was the same depth for which soil samples were taken in the 13 studies. It simulated the same solution, active, and stable inorganic P pools as SWAT, and it used the same PSP variable and 0.1 rate coefficients to initialize the P pools and transfer P between the pools. To run our model, we used reported soil P extraction data to estimate initial solution P, as described previously. We used reported soil property data to estimate initial PSP using equation 4, and then used solution P and the PSP values to estimate initial soil active and stable inorganic P using equation 1 and the SWAT assumption that stable P is four times that of active P. We simulated the same time periods as reported in the 13 studies. We simulated crop P uptake from the solution P pool by dividing reported seasonal crop uptake data into equal daily increments for the length of the reported growing season. These daily increments were then removed from solution P, as would be done in SWAT. We sim-

ulated fertilizer P addition to soil using reported application timing and rate data and initially added all fertilizer P to the solution P pool, as would be done in SWAT. We then simulated daily P transfers between the inorganic P pools using the PSP and 0.1 transfer rate coefficients as described previously for SWAT2000 or SWAT2005.

We also simulated daily P transfers using routines proposed by Vadas et al. (2006). These routines are similar to those used in SWAT but employ dynamic P transfer rate coefficients instead of the constant 0.1 coefficients used in SWAT. These dynamic rate coefficients change as a function of time after an imbalance between solution and active P begins. Vadas et al. (2006) found that dynamic rate coefficients more accurately predicted changes in solution P after a P addition to soils. When using the Vadas et al. (2006) routines, we also allowed PSP to vary with time as soil solution P and thus the PSP value calculated with equation 4 changed with time. A variable PSP value is more consistent with experimental observations that as soil total P increases over time due to excessive fertilization, a greater percentage of that P remains in a labile form (i.e., solution P in SWAT) (Allen and Mallarino, 2006; Casson et al., 2006). To simulate a dynamic PSP, we used equation 4 and allowed PSP to change as solution P varied. To allow for a variable PSP value, we kept a running average of daily solution P values up to a maximum of 1500 days and calculated PSP on a daily basis. A running average prevented extremely high or low daily solution P values (e.g., just after P fertilization) from unreasonably affecting PSP calculations.

The results in figure 3 show that overall, both the SWAT2000 and SWAT2005 routines and the routines proposed by Vadas et al. (2006), along with a variable PSP value, provided accurate predictions of long-term changes in solution P, all with Nash Sutcliffe model efficiencies of 0.95. Results between the SWAT2000 and SWAT2005 routines did not differ. However, there were distinct differences between the SWAT and Vadas et al. (2006) routines in predicting short-term (e.g., weeks to months) changes in solution P. For example, we used the different routines to simulate changes in solution P for the data of Zheng et al. (2003), who monitored changes in soil P over ten months that included four cycles of P addition at four different rates of added fertilizer and plant P uptake. Figure 4 shows measured and simulated results for the 40 kg ha⁻¹ added P rate for one of the five soils used in the study. The daily simulation results in figure 4 show that when P is added to soils, SWAT2000 routines simulate a gradual increase in solution P for 20 days and then a gradual decrease until the next P addition. These trends are because when a P addition is made in SWAT2000, all the added P is initially transferred to the active P pool and then gradually moved from active to solution P to restore equilibrium between the two pools. Solution P increases initially with time because P inputs to the solution pool are greater than outputs due to plant P uptake. The reverse is true after about 25 days. Conversely, the routines of SWAT2005 and Vadas et al. (2006) initially leave all the added P in the solution pool and gradually transfer it to the active pool. Figure 4 shows that the SWAT2005 routines will simulate less solution P than the routines of Vadas et al. (2006), primarily because of a constant PSP value that allows less P in the solution P pool.

Overall, the data in figure 4 show that the SWAT2000 and SWAT2005 P transfer routines will underpredict solution P in
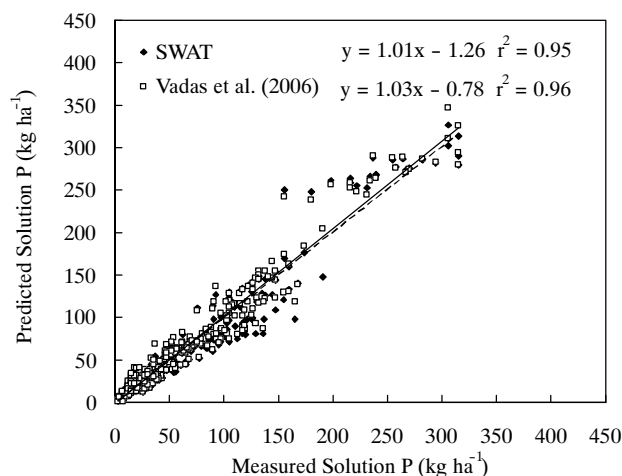
Figure 3. Measured soil labile P and soil solution P predicted using SWAT routines and routines proposed by Vadas et al. (2006). Measured data are from the 13 published studies listed in table 3.

the short-term. Since SWAT simulates dissolved inorganic P loss in runoff based on the quantity of solution P, underpredictions of solution P would in turn result in underpredictions of dissolved P loss in runoff during a several-week period after a P addition to soils. Figure 4 shows that for the SWAT2005 routines, these runoff dissolved P underpredictions may be insignificant. However, underpredictions for the SWAT2000 routines may be much more significant for at least the first 20 to 25 days after a P addition.

We constructed a spreadsheet to broadly quantify the effect of SWAT2000's underprediction of solution P on simulated dissolved P loads (kg ha^{-1}) in runoff. We simulated two soil types: high clay (540 g kg^{-1}) and low clay (130 g kg^{-1}). We initialized soil labile P to 25 mg kg^{-1} and organic carbon to 2%, calculated PSP using equation 4, and initialized active P with equation 1. We simulated a scenario of crop uptake at 50 mg kg^{-1} and fertilization at 100 mg kg^{-1} for two 365-day cycles of crop growth and fertilization. We simulated P transfer between active and solution P using the rate coefficients from SWAT2000, SWAT2005, and Vadas et al. (2006). We

randomly chose 36 d per cycle for runoff and solution P transfer to runoff to occur. We calculated dissolved P in runoff (mg L^{-1}) from solution P and a constant extraction coefficient of 0.005 (Vadas et al., 2005). Runoff randomly varied between 0.5 and 1.2 cm, which is in a range measured from natural rainfall over 14 months at a research site in central Pennsylvania (Vadas et al., 2007a). We calculated P loads in runoff (kg ha^{-1}) on an arbitrary field size of 1 ha, and summed total runoff P loads over the entire simulation. Variations in P transfer rate coefficients did not drastically change predicted dissolved P loads in runoff over the entire two-year simulation cycle. Predicted runoff P was greatest for the SWAT2005 (1.49 kg ha^{-1}) and dynamic P transfer rate coefficients (1.46 kg ha^{-1}), but about 6% less for the SWAT2000 transfer coefficients (1.38 kg ha^{-1}). However, for the first 30 d after P addition, predicted runoff P using the SWAT2000 rates was 30% less for the high clay soil and 37% less for the low clay soil.

CONCLUSIONS

We used data from 40 published studies to validate the ability of the soil inorganic P routines in SWAT2000 and SWAT2005 to initialize the quantity of P in the soil pools and predict long-term and short-term changes in soil solution P. Results show that currently published equations used to estimate the soil PSP parameter and SWAT's method of summing four soil P pools underpredict soil total P. An underprediction of soil total could subsequently result in underprediction of P loss in runoff with eroded sediment. Conversely, the proposed alternative for estimating soil total P, which includes a new equation to estimate the soil PSP parameter and includes the solution P pool when summing soil P pools, resulted in accurate predictions of soil total P for 484 topsoils samples from 35 published studies. Results show that both the SWAT2000 and SWAT2005 routines and the routines proposed by Vadas et al. (2006) for simulating changes in soil inorganic P pools were able to accurately predict long-term changes in soil solution P. However, simulation results show that the SWAT2000 routines may underpredict solution P for several weeks after P is added to soils. This could result in a 30% to 37% underprediction of dissolved inorganic P loss in runoff soon after a P application to soils. The routines in SWAT2005 and those proposed by Vadas et al. (2006) would not result in similar underpredictions.

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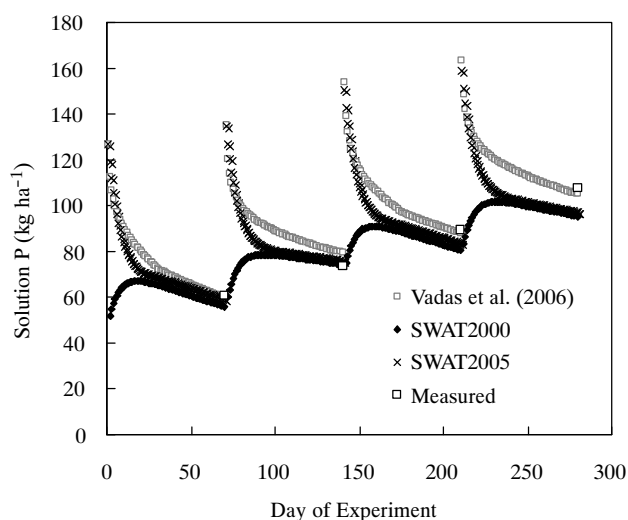
Figure 4. Soil labile P measured every 70 days during a fertilizer and plant uptake study and daily soil solution P predicted for the experimental conditions using SWAT routines and routines proposed by Vadas et al. (2006). Measured data are from Zheng et al. (2003).

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